Laser Frequency Stabilization for GRACE-2

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- Co-Is:
  - W. Klipstein, N. Yu (JPL), M. Stephens, J. Leitch (BATC)
- Collaborators:
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- Cavity/enclosure development
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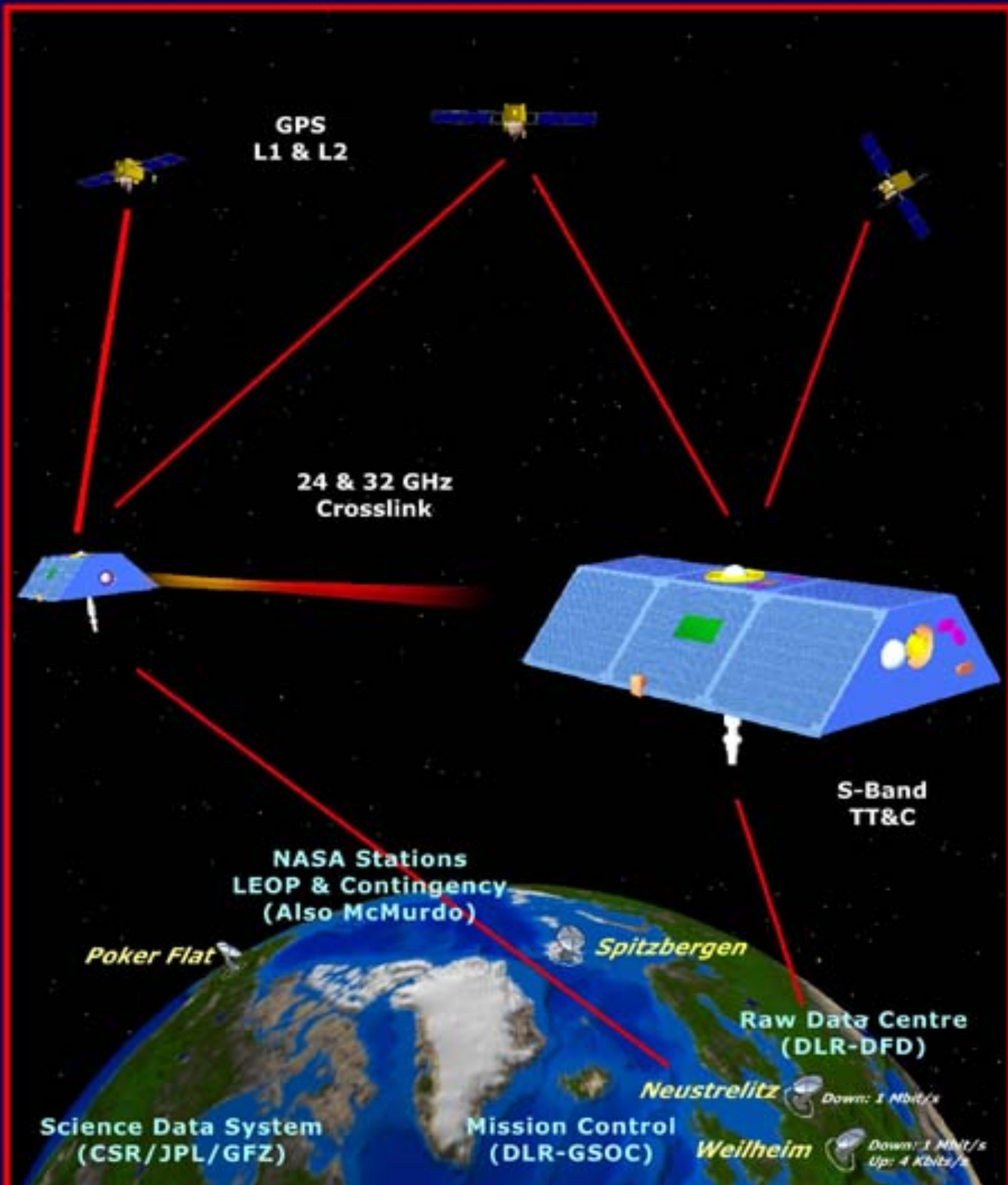


GRACE Mission

Science Goals

High resolution, mean & time variable gravity field mapping for Earth System Science applications.

Mission Systems

Instruments

- KBR (JPL/SSL)
- ACC (ONERA)
- SCA (DTU)
- GPS (JPL)

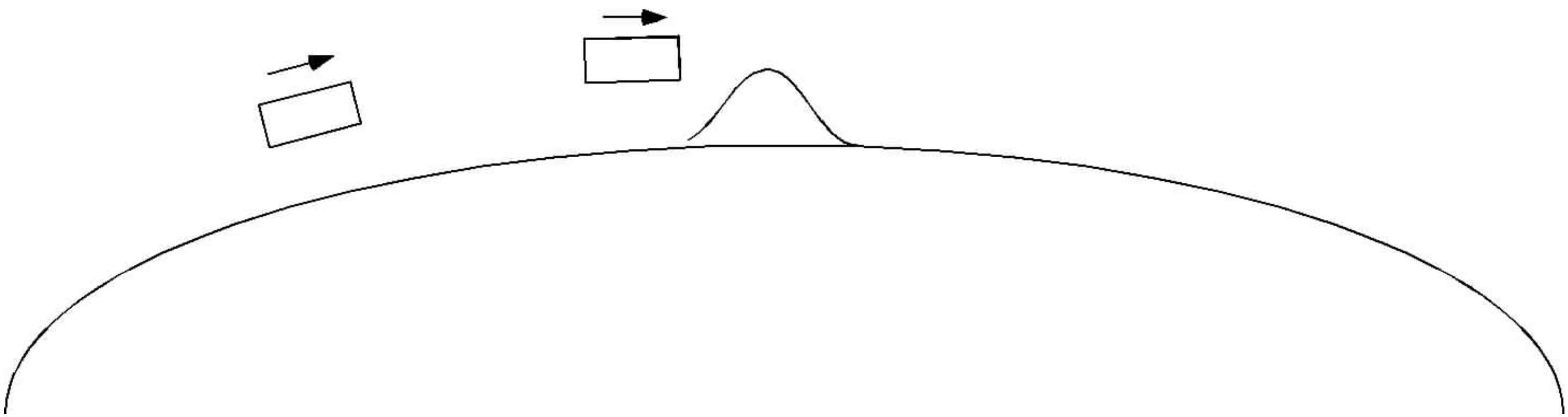
Satellite (JPL/DSS)
Launcher (DLR/Eurockot)
Operations (DLR/GSOC)
Science (CSR/JPL/GFZ)

Orbit

Launch: March 2002
Altitude: 485 km
Inclination : 89 deg
Eccentricity: ~0.001
Lifetime: 5 years
Non-Repeat Ground Track
Earth Pointed, 3-Axis Stable

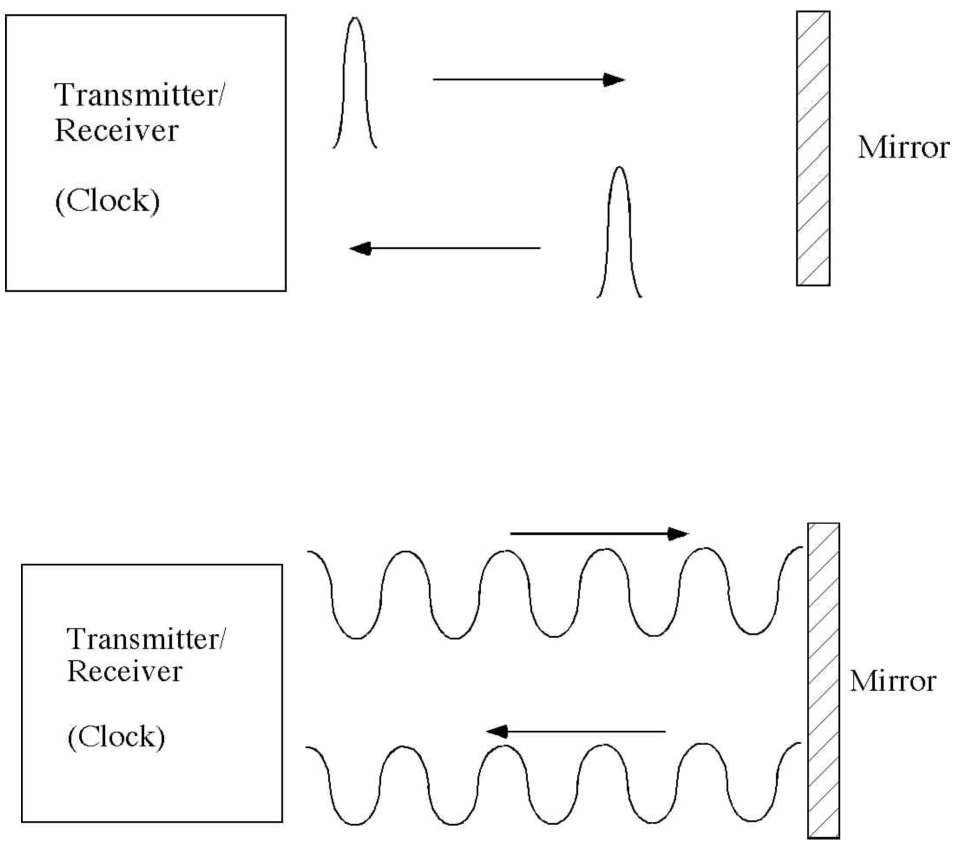
GRACE Measurement Concept

- Earth gravity features affect lead/trailing spacecraft at different times
  - Lead spacecraft encounters feature first
    - e.g. lead spacecraft speeds up towards mountain
      - Range to trailing spacecraft increases
  - Any unknown non-gravity forces acting on spacecraft also affect range
    - Calibrated out using accelerometer or drag-free sensor system



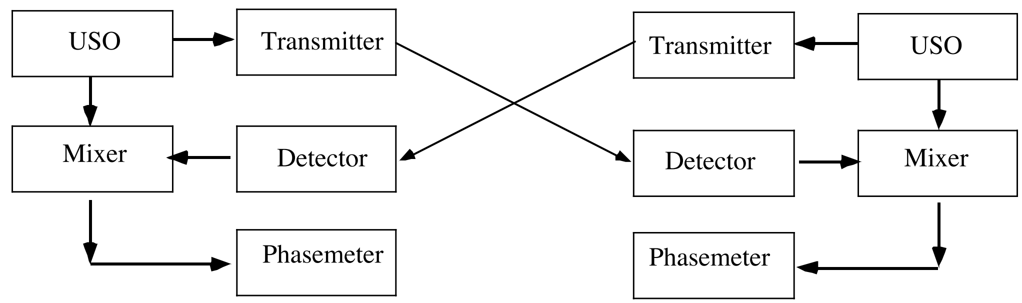
Ranging Measurement Methods

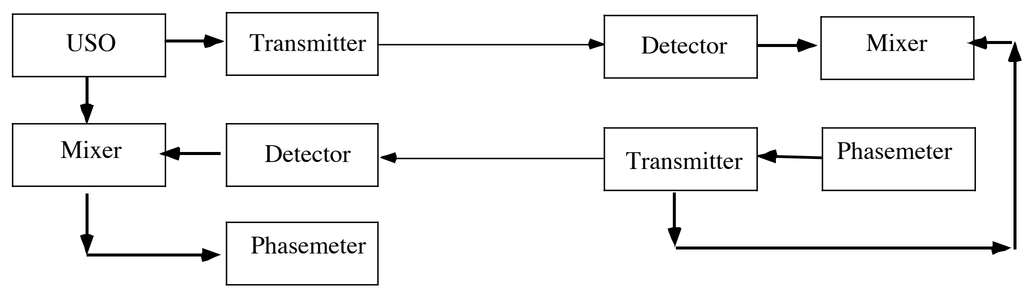
- Range is determined by round-trip light time
  - Pulsed light is used in SLR/LLR where photon rates are low
  - Coherent signals allow use of phase delay for higher accuracy
    - Range ambiguity by integer number of wavelengths can be resolved with modulation if required



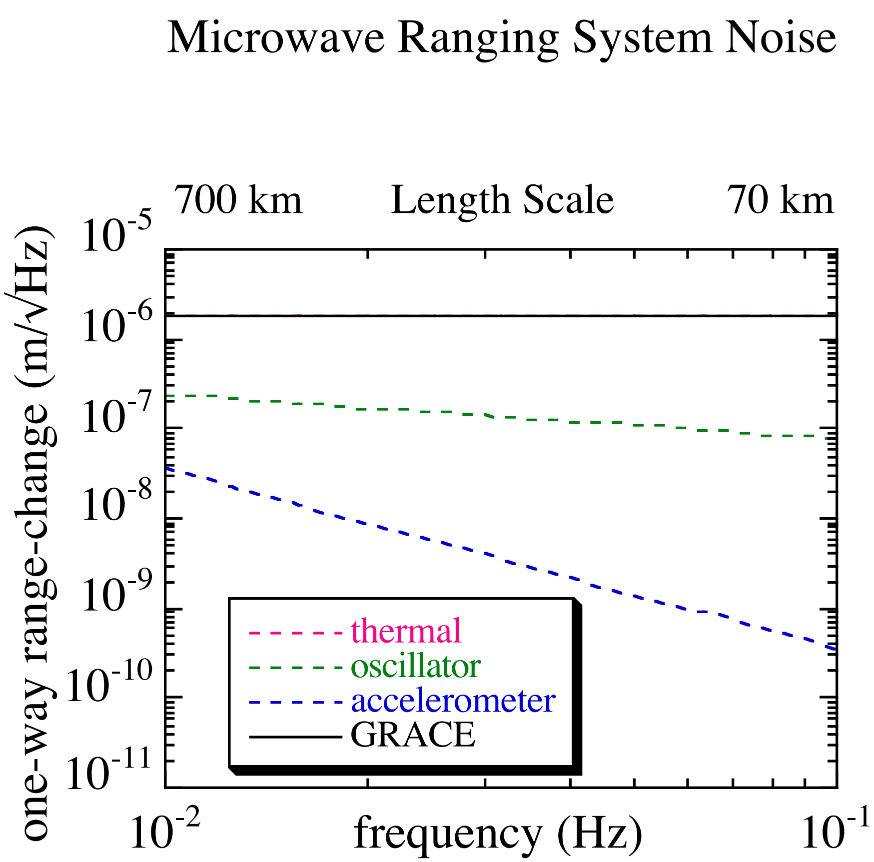
Dual-one-way versus Transponding

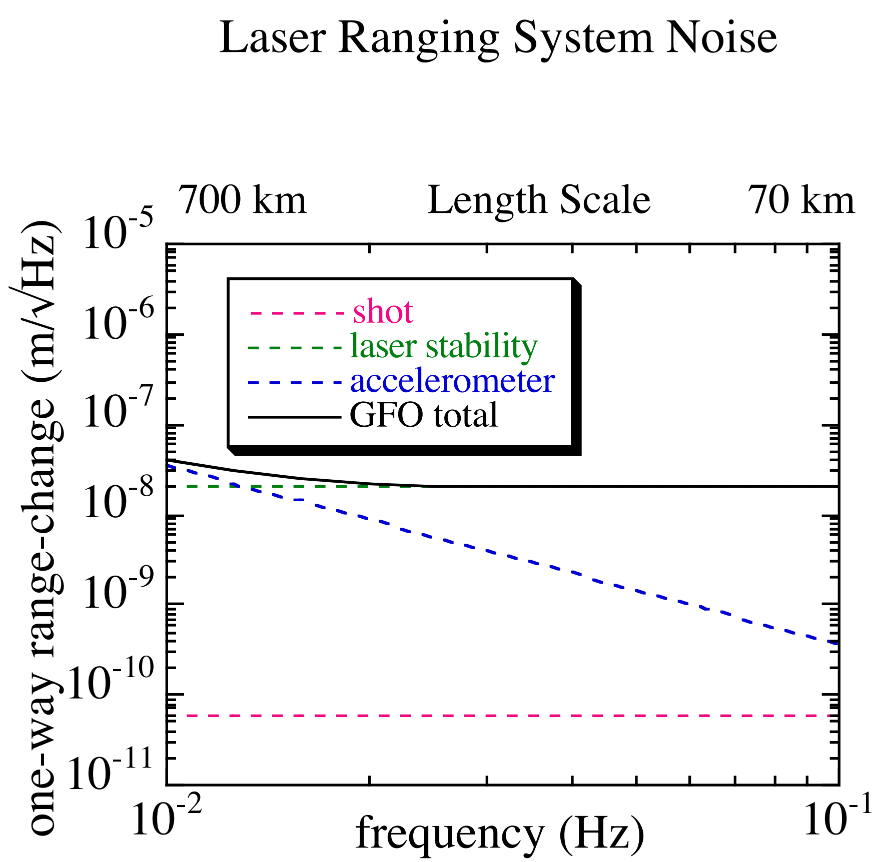
- GRACE uses independent transmission/detection at each spacecraft
  - Combination of data on ground determines range
- Laser ranging will lock laser to frequency reference on one spacecraft and lock laser to received laser on seconds s/c
  - Otherwise laser frequencies would be too far apart
  - Fast phase meter needed for locking function





Microwave and Laser Ranging Sensitivity



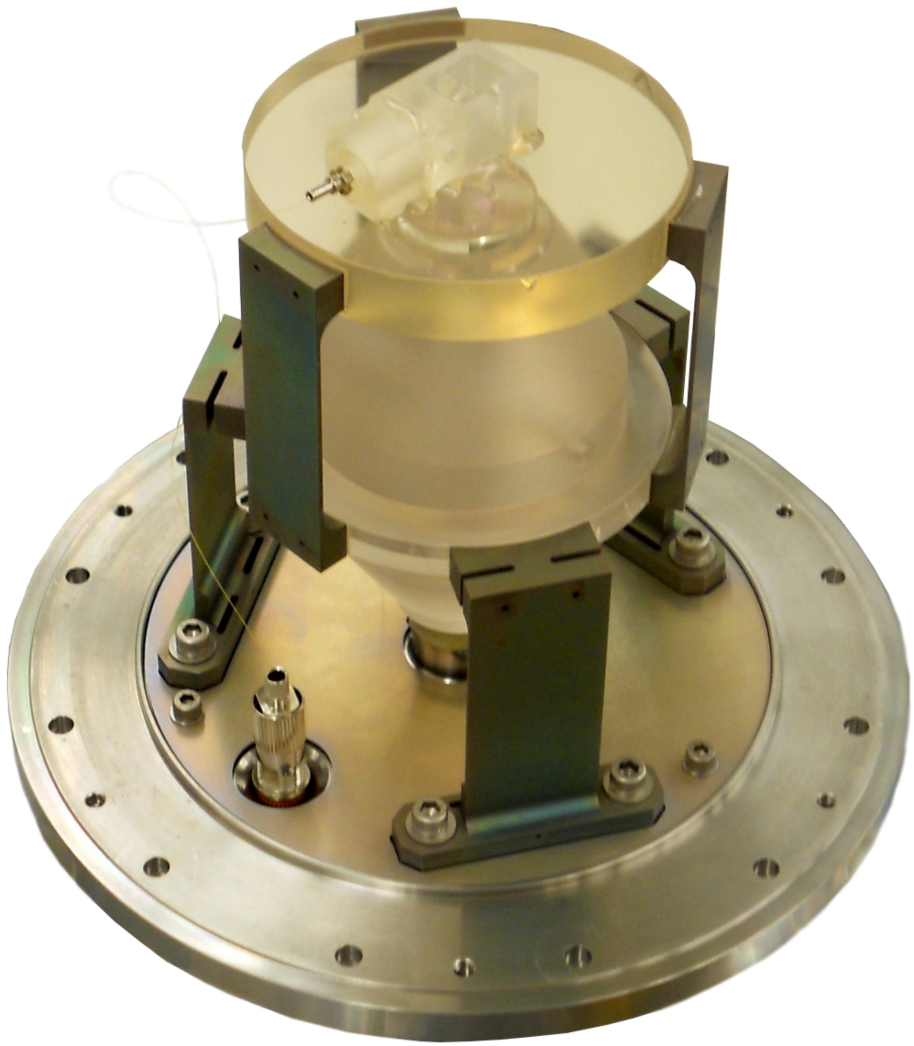


Optical Cavity Frequency Reference

- Stabilize laser frequency by locking wavelength to thermally stable optical cavity
  - ULE glass has ultra-low thermal-expansion coefficient
  - Isolate from external temperature fluctuations

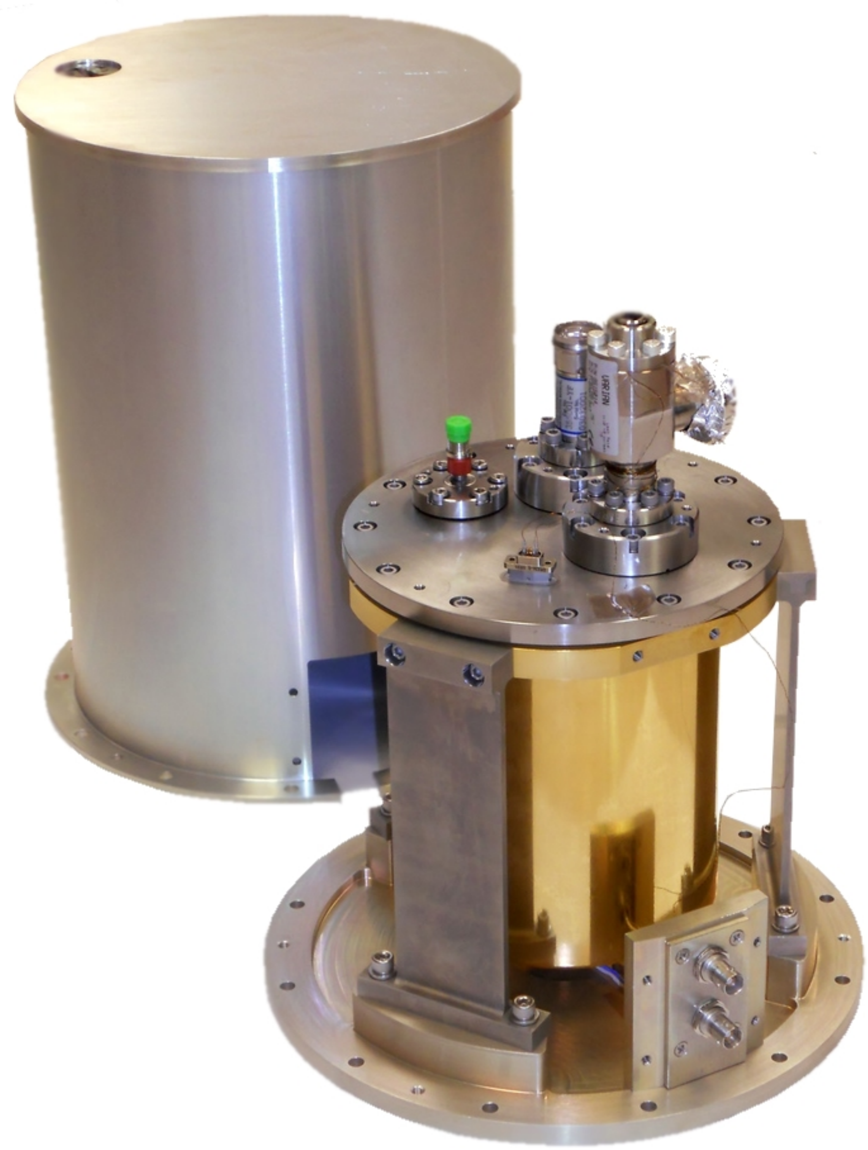
Cavity Mount Design

- Cavity is mounted using flexures bonded to cavity central ring
  - Flexure material (Ti) and stiffne chosen to provide support and maintain alignment for launch and minimize thermo-elastic effects on cavity
- Optics for injecting laser light into cavity via fiber are also mounted using flexures



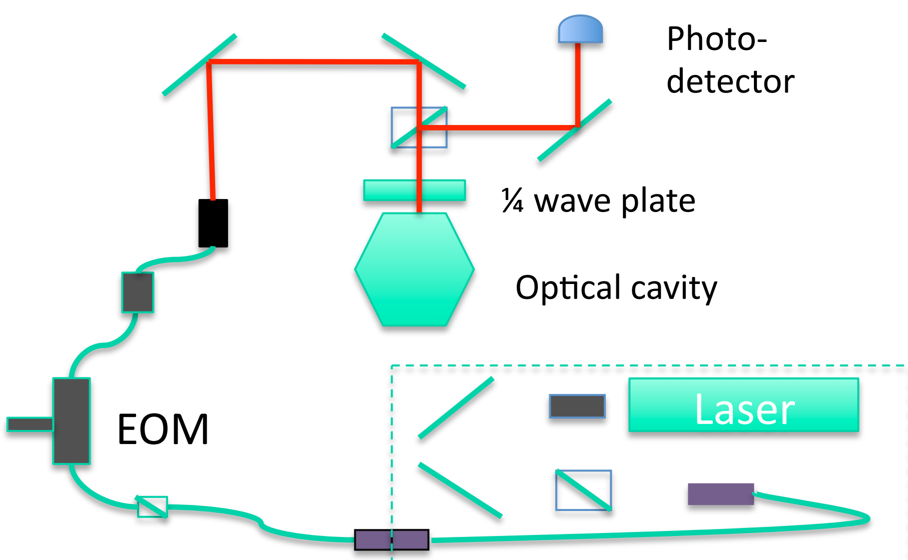
Thermal Isolation Enclosure

- Two concentric shells surround the cavity and optics to isolate them from external thermal
- Size and mass of laser frequency stabilization subsystem has been iterated with GRACE spacecraft team to ensure compatibility
- Inner shell forms a vacuum enclosure to avoid gas pressure fluctuations and contamination
  - Vacuum gauge and valve included for development will be replaced with vent-to-space actuator for flight



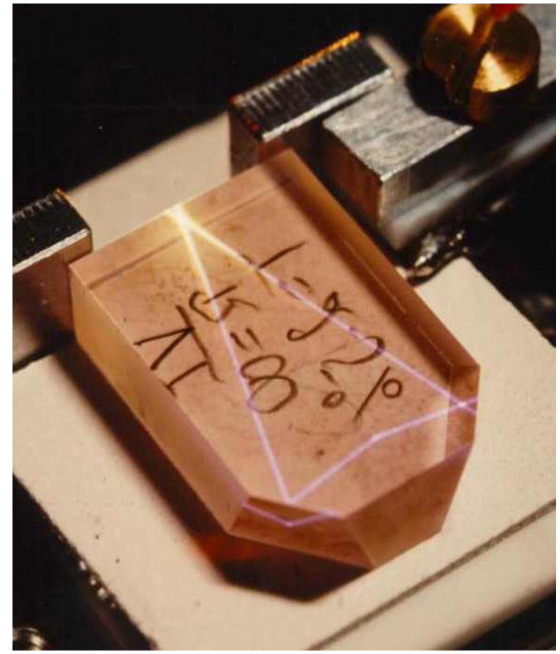
Laser Locking to Optical Cavity

- Laser locked to cavity using Pound-Drever-Hall technique
  - Light resonance occurs when cavity length is integer number of wavelengths
    - Laser frequency stability is directly related to stability of length of cavity
  - Cavity is made of material with low thermal expansion coefficient
  - Light exiting cavity compared with light entering cavity
  - Requires electro-optical modulator to add phase-modulation to laser beam
    - Difference in modulation signal gives laser correction to match cavity

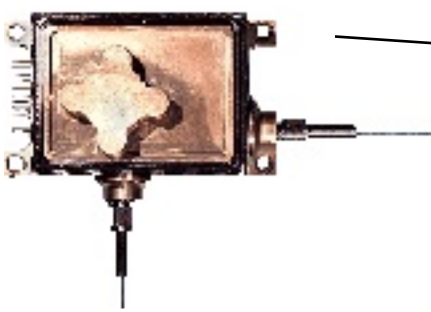


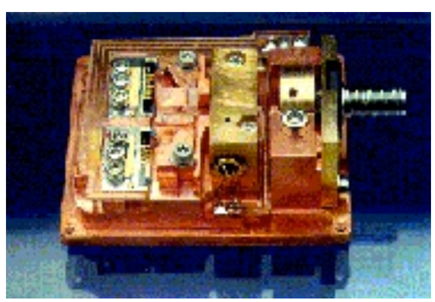
Tunable Laser

- Non-planar ring oscillator (NPRO) Nd:YAG laser provides tunability for locking to cavity
  - Laser wavelength adjusted by changing dimensions of YAG crystal using PZT glued to crystal and thermal adjustment
- Space-qualified NPRO laser available from Tesat Spacecom



NPRO laser head

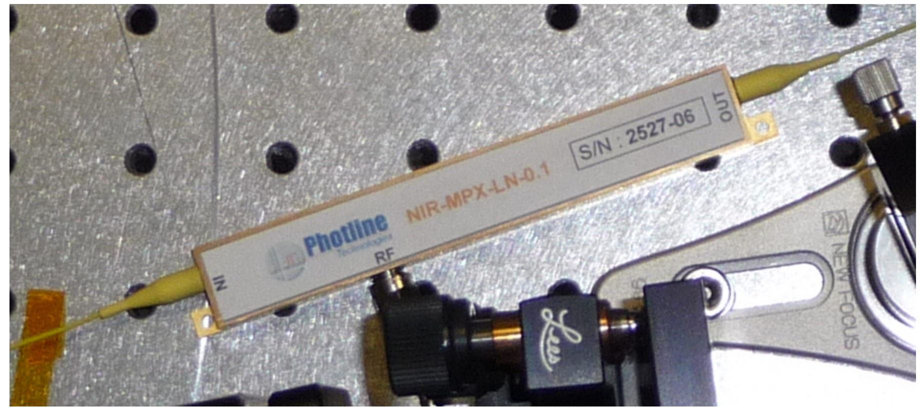




Laser pump diode assembly

Electro-Optical Modulator

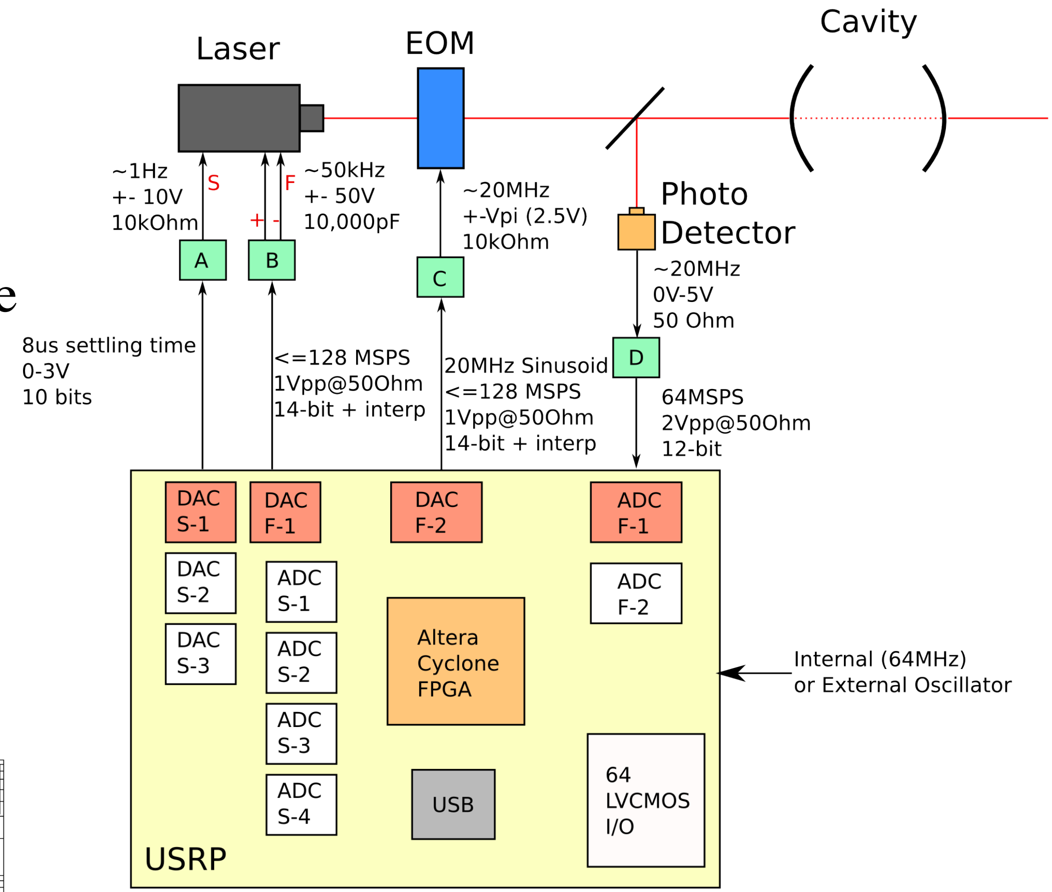
- Several companies make EOM suitable for use in space
- Selected unit from Photline has inexpensive laboratory model traceable to flight model
  - Tested to show meets locking requirements

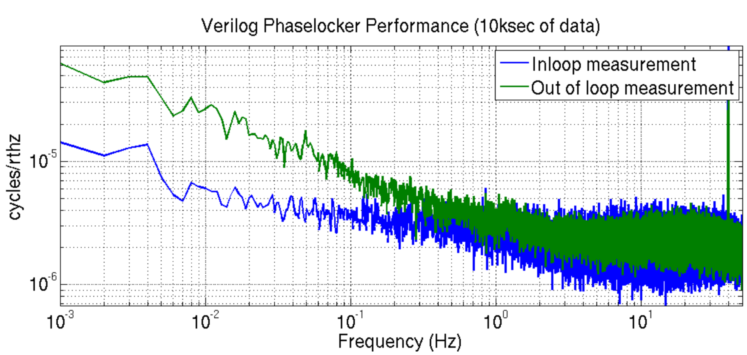


Selected electro-optical modulator

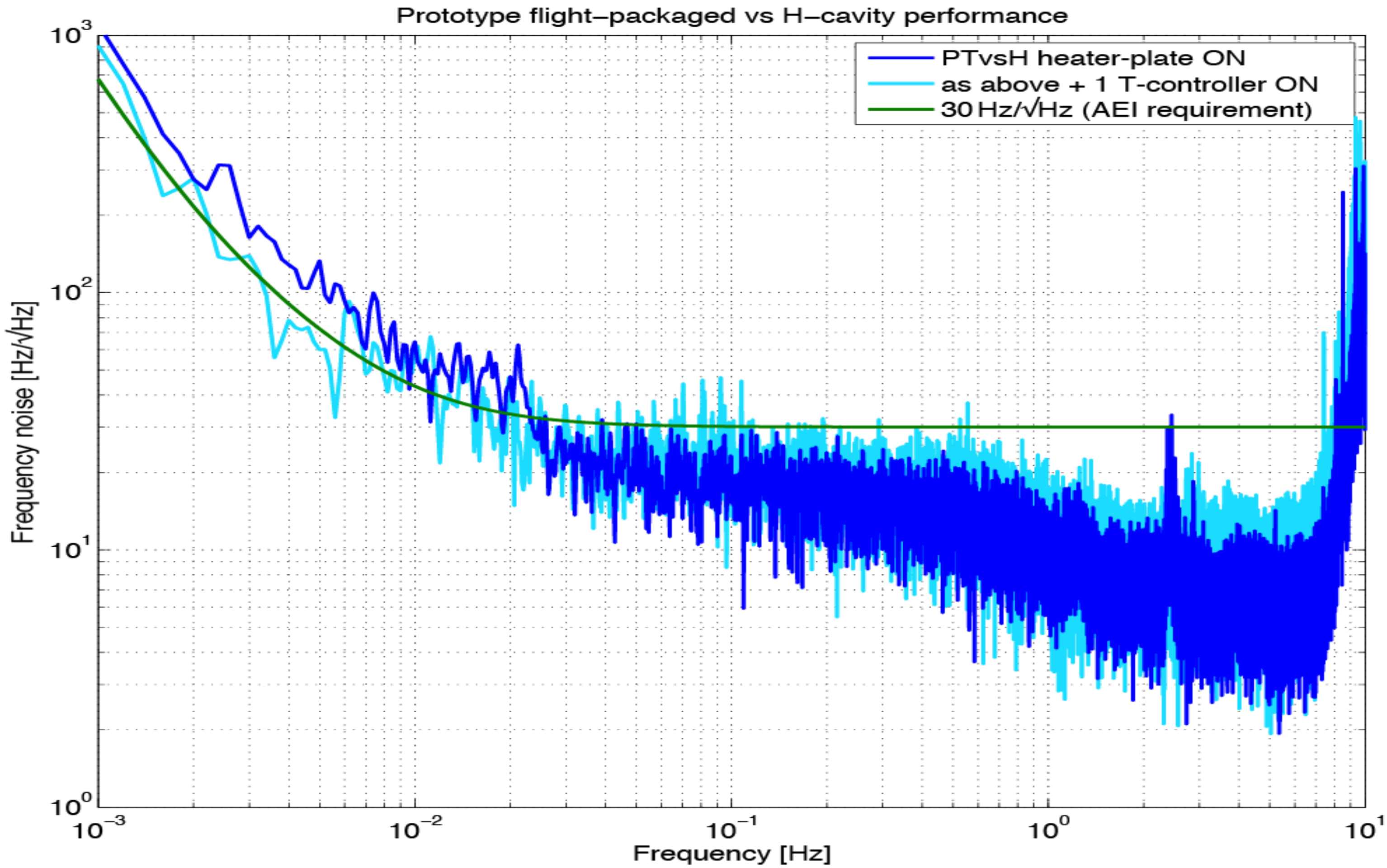
Breadboard Locking Electronics

- Commercial FPGA evaluation board used for development and testing of laser locking algorithms
  - ADC for sampling interference signal from photodiode
  - DACs used to adjust laser crystal frequency via PZT and temperature





Subsystem Performance Results



Frequency stability measured with cavity in simulated spacecraft thermal environment
Interior panel temperature variation +/- 1°C

Environmental Test Results

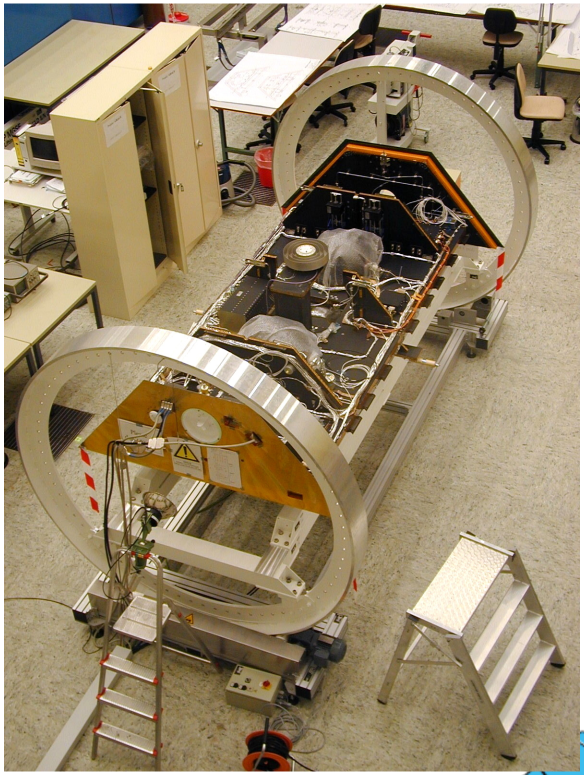
- Breadboard cavity thermal tests showed a slight misalignment occurred at highest temperatures
  - Traced to adhesive glass transition at 50C
- Prototype cavity assembled is improved processes
  - Successfully passed thermal and vibration tests
- Cavity assembly is at TRL-6

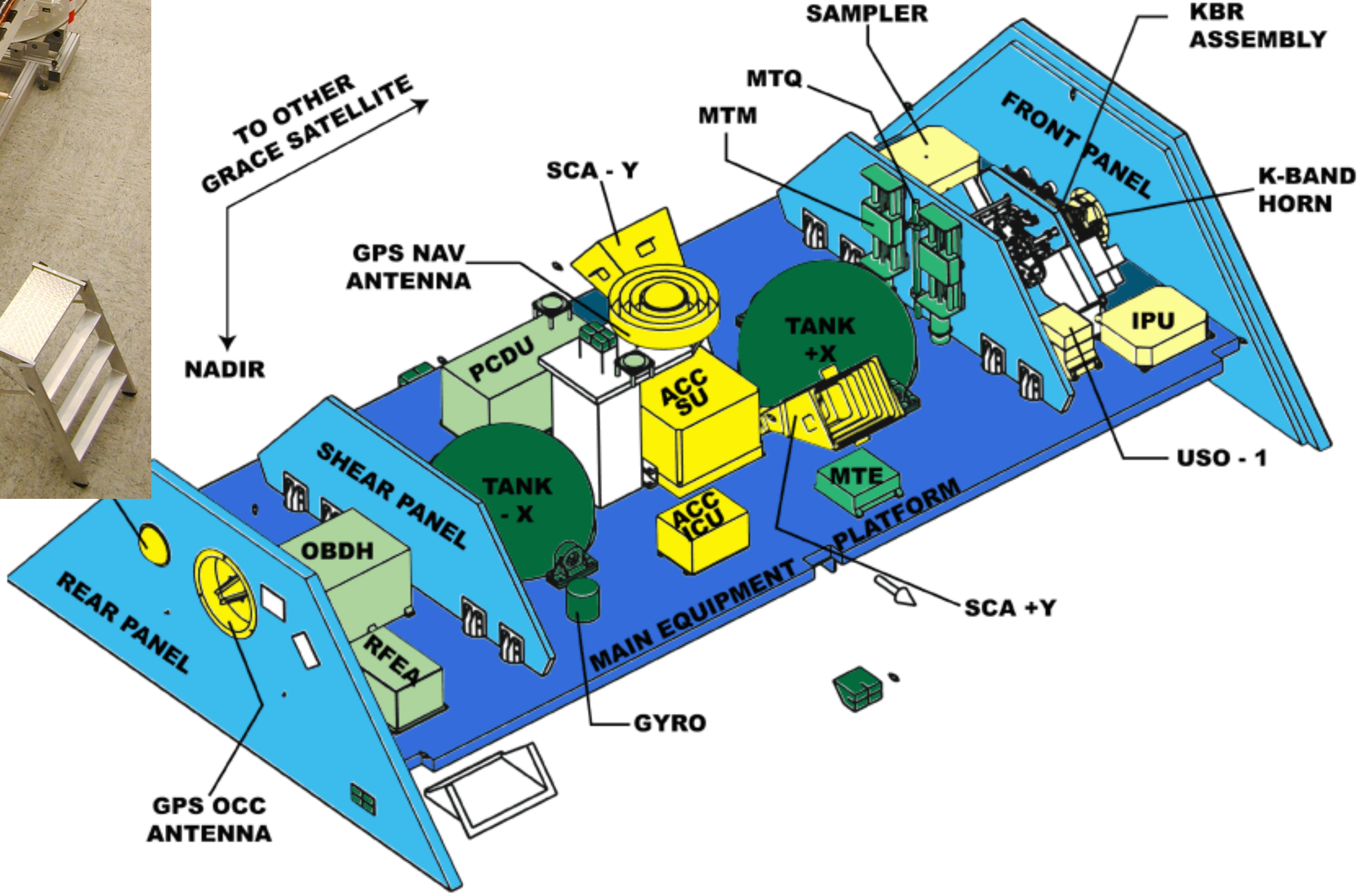
- EOM thermal test passes, vibration test pending
- Electronics prototype still in assembly

Future Plans

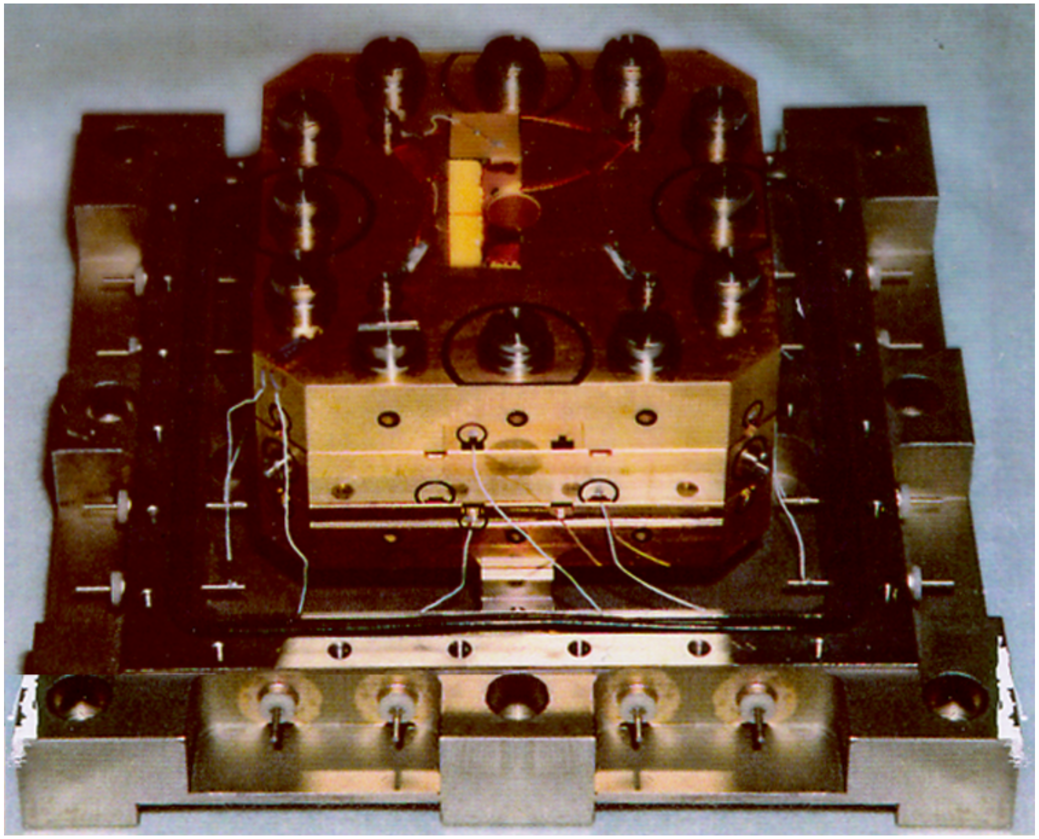
- Prototype electronics are in final assembly
  - Performance and environmental tests planned to establish TRL-6
- Functional system-level test planned with inter-spacecraft optics from IIP-02
- GRACE-FO project started June 2011 with laser ranging included as technology demonstration
  - Will include cavity and electronics developed under IIP-07
    - Cavity enclosure needs to be slightly modified to fit allocated volume
  - Optical benches, beam steering mirror and routing optics to be provided by Germany
  - Beam steering and initial acquisition are major system-level challenges remaining

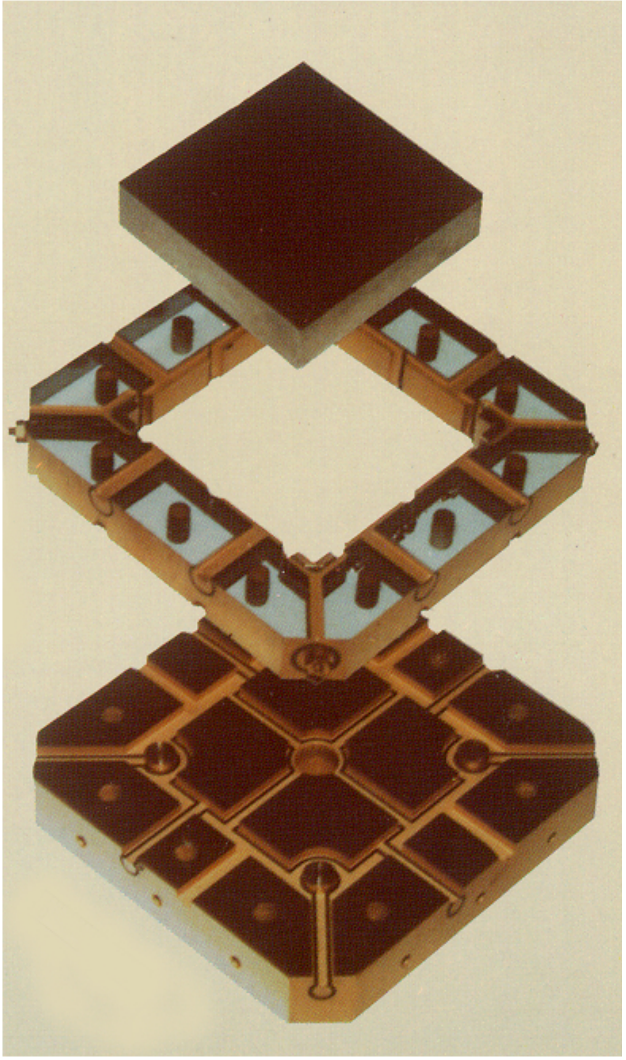
GRACE Spacecraft





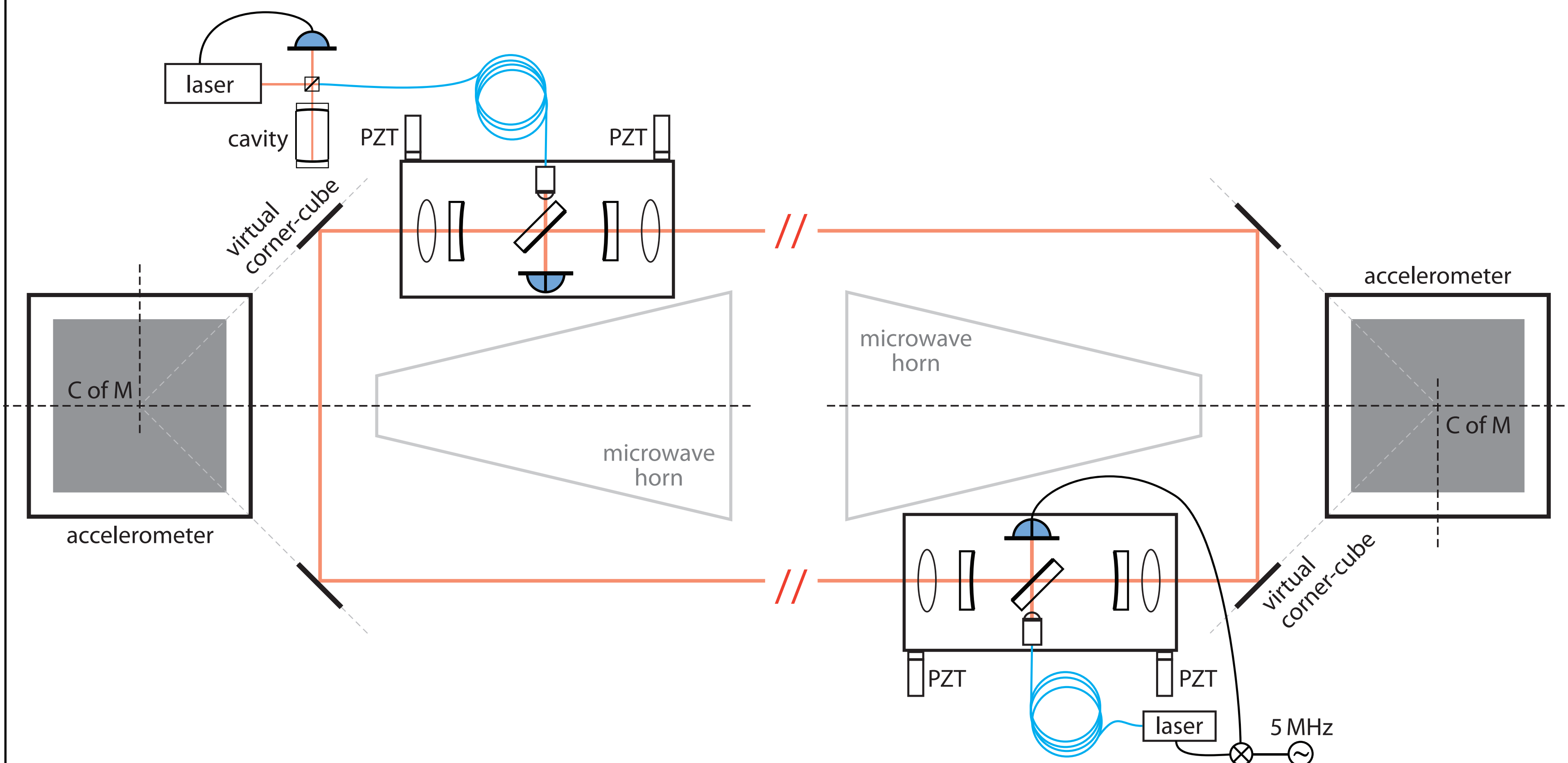
SuperSTAR Accelerometer



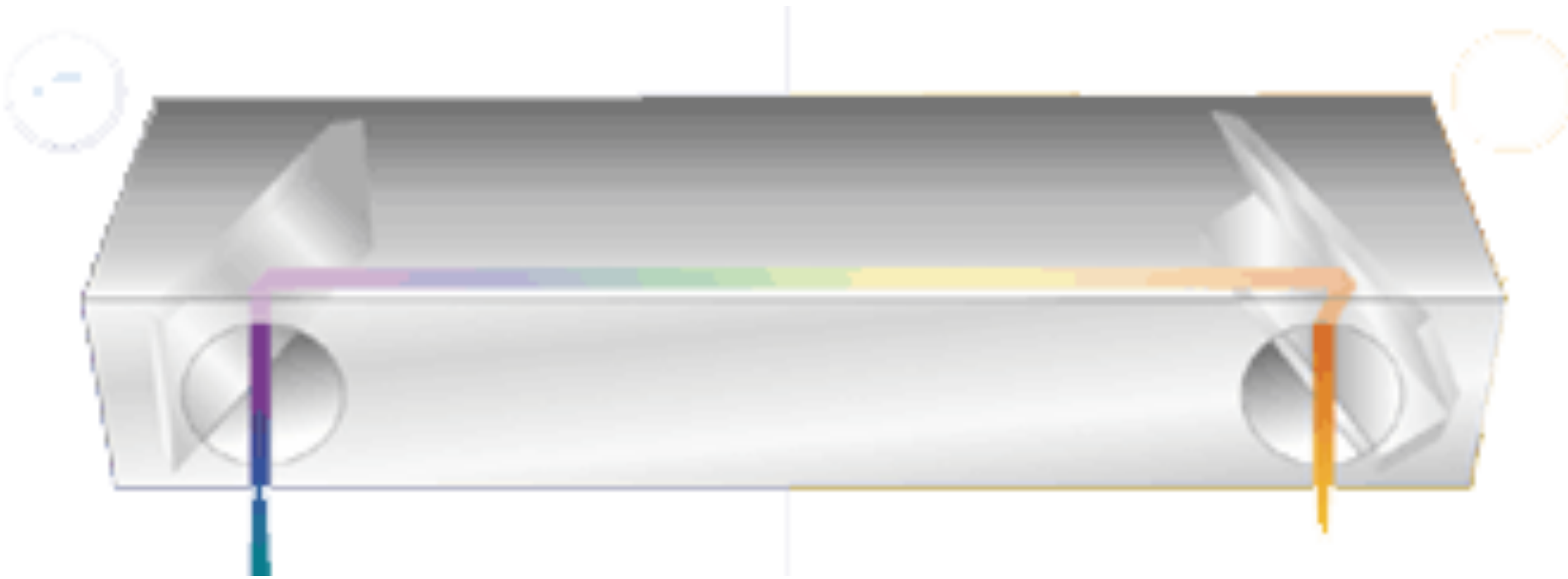


ONERA

Racetrack Configuration



Lateral Transfer Hollow Retroreflector™



IRT Optical Bench